MULTIPLE INTERACTIONS

A new model for the underlying event

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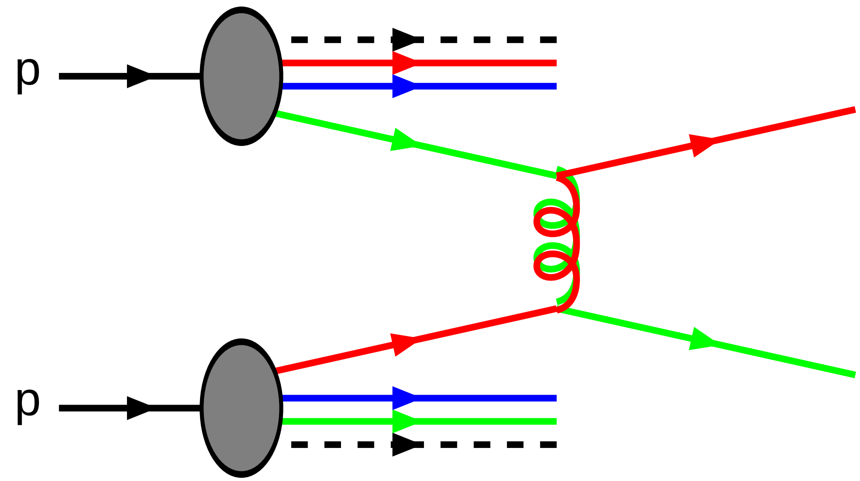
1. Basic Phenomenology.
2. Towards a realistic model $\longrightarrow$ PYTHIA 6.3.
   (hep-ph/0310315, hep-ph/0308153, + in prep...)
3. Outlook.

The Underlying Event

- Composite nature of hadrons (+ γ) $\Longrightarrow$ collisions with multiple parton–parton interactions possible.
- Even for proton–proton, underlying event (UE) is not (yet) well understood.
- At the LHC, min-bias and UE in pp collisions will:
  - Allow to probe partonic substructure of protons.
  - Present a background to other physics studies.
- Lots of data $\to$ great topic for phenomenology right now. (maybe learn about γ and heavy ions too?)

Consider just QCD $2 \to 2$ scattering:



$$\mathrm{qq'} \to \mathrm{qq'}$$
$$\mathrm{q\bar{q}} \to \mathrm{q'\bar{q}'}$$
$$\mathrm{q\bar{q}} \to \mathrm{gg}$$
$$\mathrm{qg} \to \mathrm{qg}$$
$$\mathrm{gg} \to \mathrm{gg}$$
$$\mathrm{gg} \to \mathrm{q\bar{q}}$$

Infrared Divergent:

$$\sigma_{2\to2}(p_{\perp\mathrm{min}}) = \int_{p_{\perp\mathrm{min}}}^{\sqrt{s}/2} \frac{\mathrm{d}\sigma}{\mathrm{d}p_\perp}\mathrm{d}p_\perp \propto \frac{1}{p^2_{\perp\mathrm{min}}}$$

Basic Phenomenology

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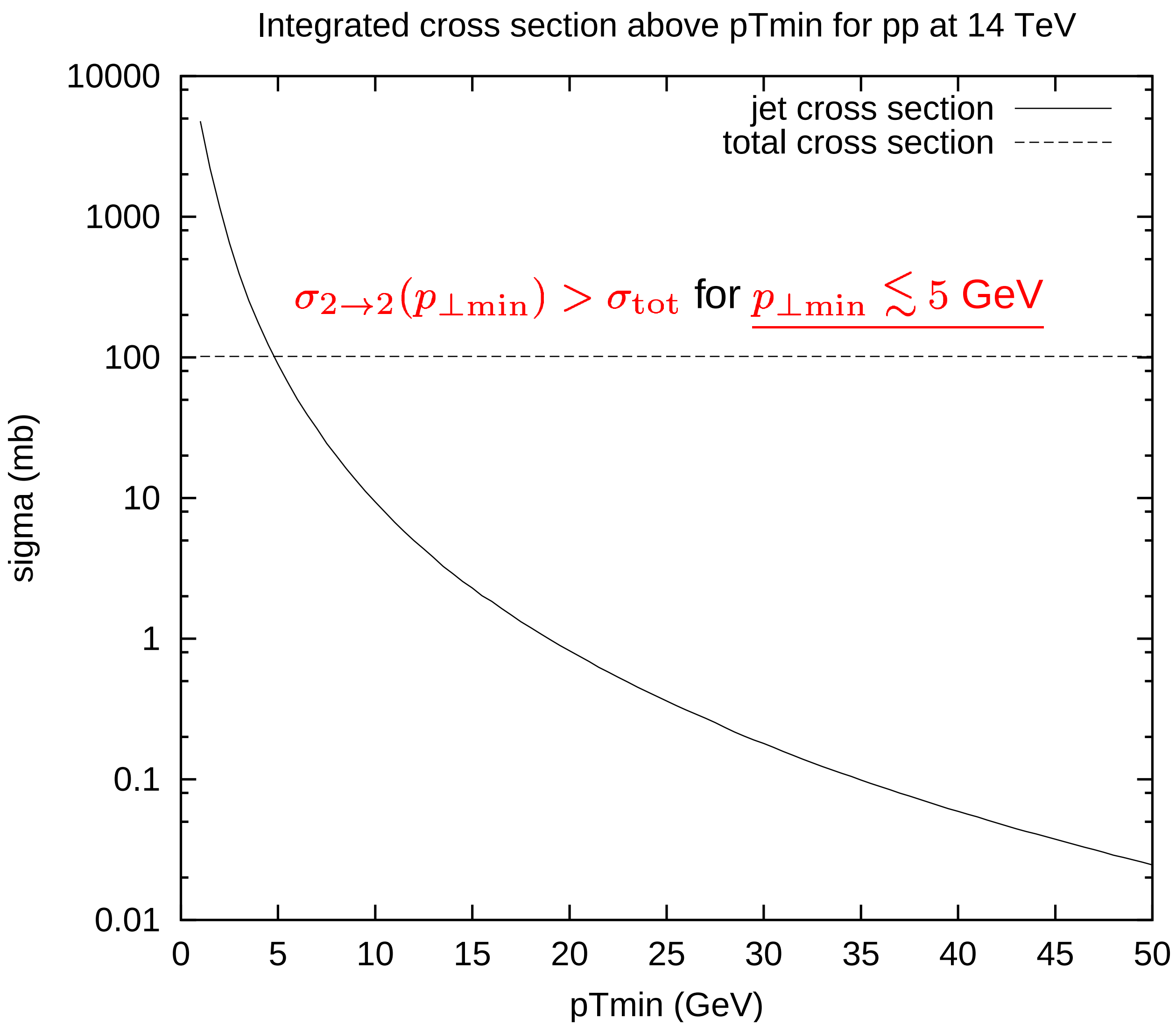


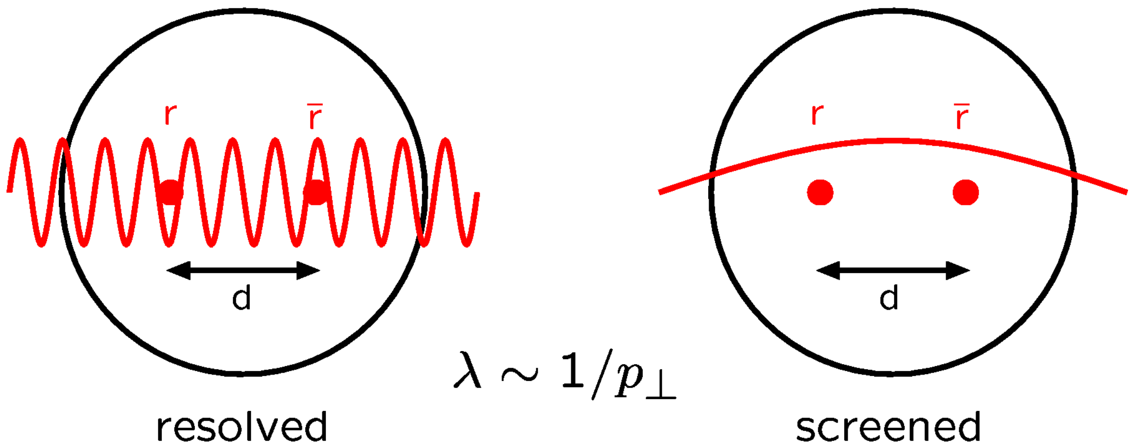
Basic Phenomenology

1:

- σ_{tot}: hadron-hadron collisions. $\sigma_{\mathrm{tot}} = \sum_{n=0}^{\infty} \sigma_n$
- $\sigma_{2\to 2}$: parton–parton collisions. $\sigma_{2\to 2} = \sum_{n=0}^{\infty} n\,\sigma_n$
- Many interactions / event: $\langle n \rangle > 1$

2:

- Breakdown of perturbative QCD, colour screening.



$p_{\perp 0} \sim 2$ GeV ($p_{\perp 0}$: inverse colour screening distance.)

Why care?

$$\langle n \rangle_{\text{Tevatron}} \sim 2 - 4, \quad \langle n \rangle_{\text{LHC}} \sim 5 - 10$$

Multiple interactions are responsible for:

- ☞ Large fraction of total multiplicity.
- ☞ Fluctuations to large multiplicities.
- ☞ Rapidity correlations in activity.
- ☞ Multiple (mini)jet production.
- ☞ Jet profile and jet pedestal.
- ☞ Shifts in jet energy scale.

$\Longrightarrow$ $\boxed{\text{precision physics involving jets or underlying events impossible without good understanding of multiple interactions.}}$

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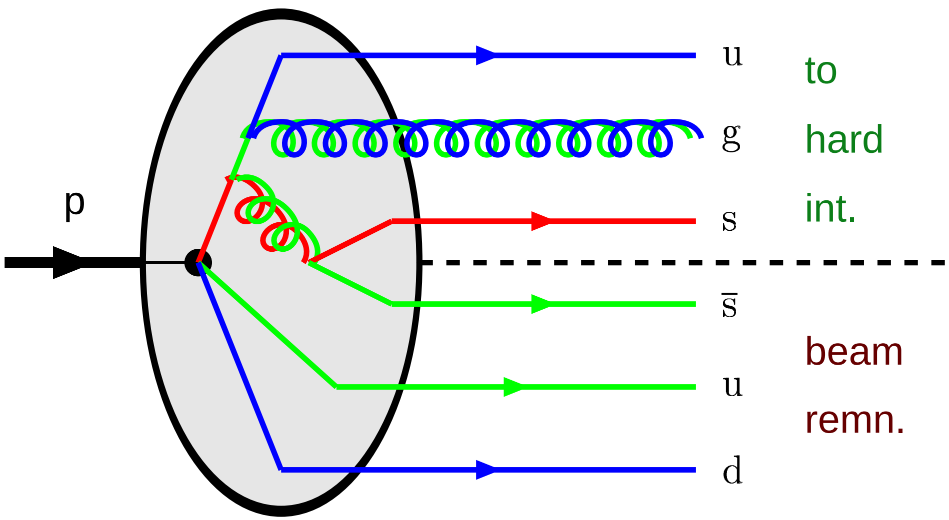
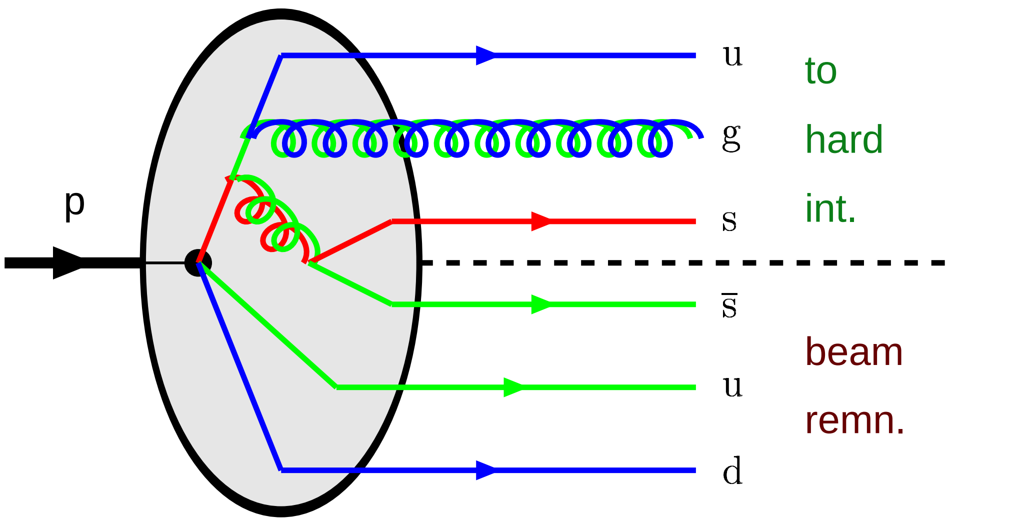
This talk is about PYTHIA 6.3

Towards a realistic model



How are the hard scattering initiators and beam remnant partons correlated:

Towards a realistic model



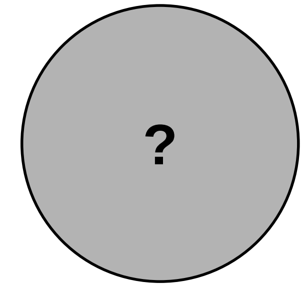
How are the hard scattering initiators and beam remnant partons correlated:

- ☞ In impact parameter?
- ☞ In flavour?
- ☞ In longitudinal momentum?
- ☞ In colour?
- ☞ In (primordial) transverse momentum?

(How) are the showers correlated / intertwined?

Correlations in flavour and $\mathbf{x}_i$

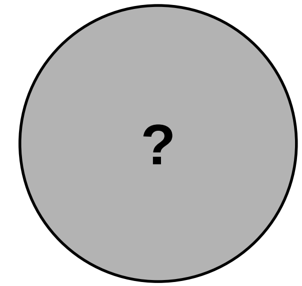
Consider a hadron:



P to find flavours $i_1 \ldots i_n$ with momenta $x_1 \ldots x_n$ in hadron probed at scales $Q_1 \ldots Q_n$:

$$f_{i_1 \ldots i_n}(x_1 \ldots x_n, Q_1^2 \ldots Q_n^2)$$

Correlations in flavour and x_i



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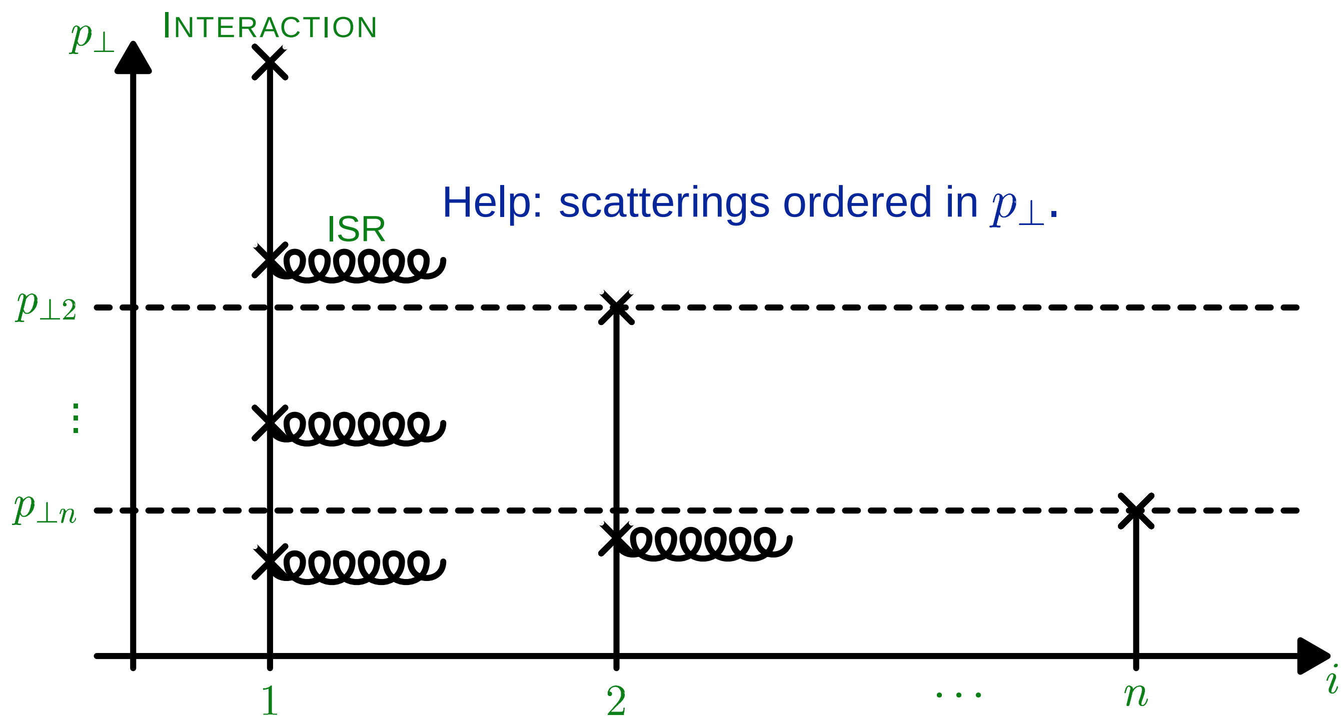
Experimentally, what we got is $n = 1$.



Correlations in flavour and x_i

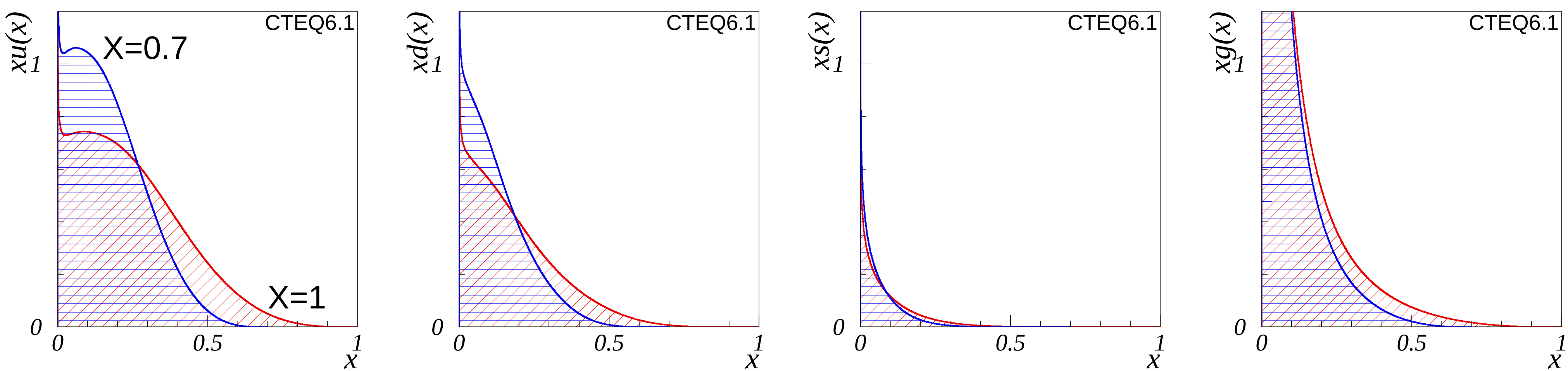
Q: What are the pdf's for a proton with 1 valence quark, 2 sea quarks, and 5 gluons knocked out?

1. Overall momentum conservation (old):

Ensured by 'squeezing' the distributions in x.

For the n'th scattering:

$$x \in [0, X] \;\; ; \;\; X = 1 - \sum_i^{n-1} x_i \implies f_n(x) \sim \frac{1}{X} f_0\left(\frac{x}{X}\right)$$



Correlations in flavour and x_i

Q: What are the pdf's for a proton with 1 valence quark, 2 sea quarks, and 5 gluons knocked out?

Normalization and shape NEW!:

- If valence quark knocked out.

  $\rightarrow$ Impose counting rule: $\int_0^X q_{fn}^{\mathrm{val}}(x,Q^2)\,\mathrm{d}x = N_{fn}^{\mathrm{val}}$.

- If sea quark knocked out.

  $\rightarrow$ Postulate "companion antiquark": $\int_0^{1-x_s} q_f^{\mathrm{cmp}}(x;x_s)\,\mathrm{d}x = 1$.

- But then momentum sum rule is violated:

$$\int_0^X x\Big(\sum_f q_{fn}(x,Q^2) + g_n(x,Q^2)\Big)\mathrm{d}x \neq X$$

$\rightarrow$ Assume sea+gluon fluctuates up when a valence quark is removed and down when a companion quark is added.

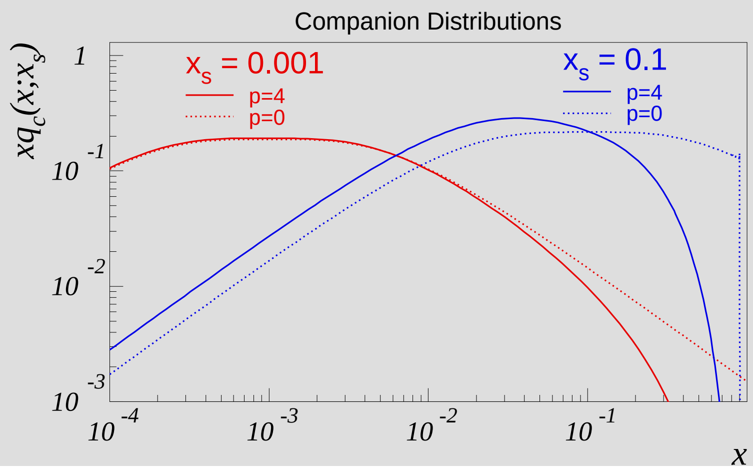
Remnant PDFs

$$\text{quarks}: \quad q_{fn}(x) = \frac{1}{X}\left[\frac{N^{\mathrm{val}}_{fn}}{N^{\mathrm{val}}_{f0}}\, q^{\mathrm{val}}_{f0}\left(\frac{x}{X}, Q^2\right) + a\, q^{\mathrm{sea}}_{f0}\left(\frac{x}{X}, Q^2\right) + \sum_j q^{\mathrm{cmp}_j}_{f0}\left(\frac{x}{X}; x_{s_j}\right)\right]$$

$$q^{\mathrm{cmp}}_{f0}(x; x_s) = C\, \frac{\tilde{g}(x + x_s)}{x + x_s}\, P_{\mathrm{g}\to q_f \bar{q}_f}\left(\frac{x_s}{x + x_s}\right) \quad ; \quad \left(\int_0^{1-x_s} q^{\mathrm{cmp}}_{f0}(x; x_s)\, \mathrm{d}x = 1\right)$$

$$\text{gluons}: \quad g_n(x) = \frac{a}{X}\, g_0\left(\frac{x}{X}, Q^2\right)$$

$$a = \frac{1 - \sum_f N^{\mathrm{val}}_{fn} \langle x^{\mathrm{val}}_{f0}\rangle - \sum_{f,j} \langle x^{\mathrm{cmp}_j}_{f0}\rangle}{1 - \sum_f N^{\mathrm{val}}_{f0} \langle x^{\mathrm{val}}_{f0}\rangle}$$

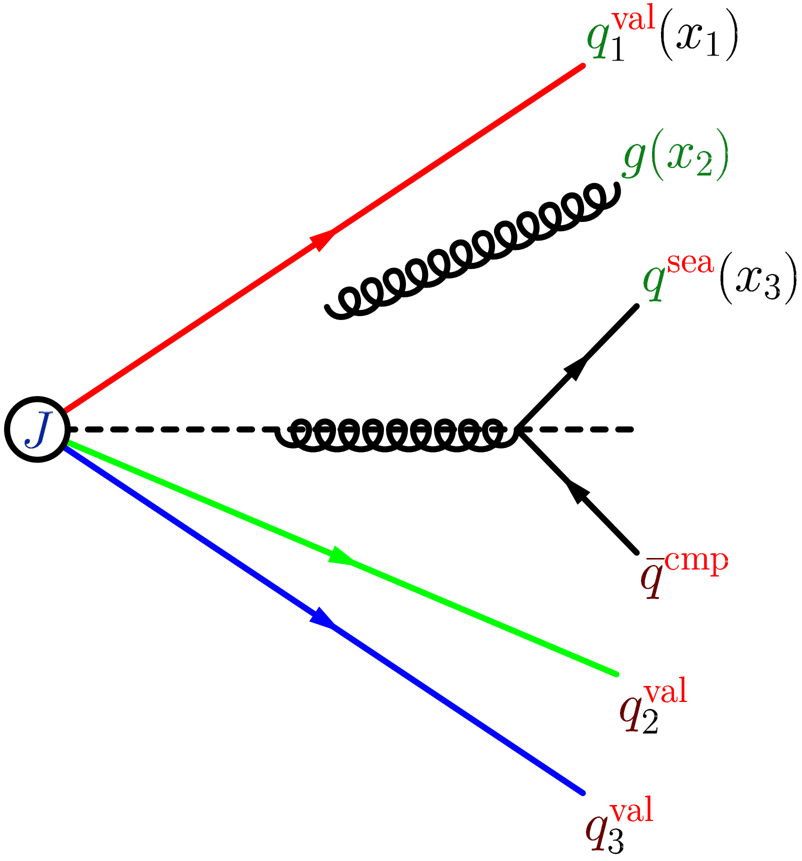


Used to select a sequence of hard scatterings, with parton showers.

Finally, flavour conservation $\Rightarrow$ flavour content of beam remnant.

Hooking it up

Assume initial valence topology + gluons (one parent gluon for each sea pair). *Some* colour flow must exist, but no perturbative information available.



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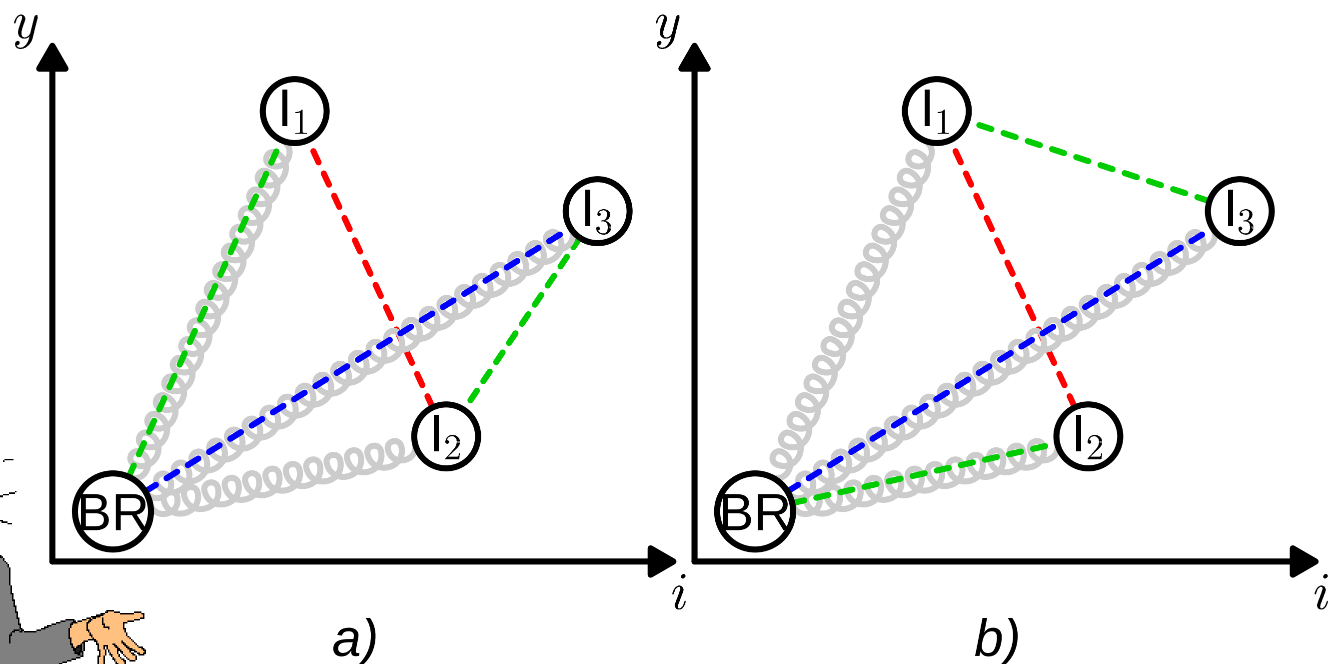
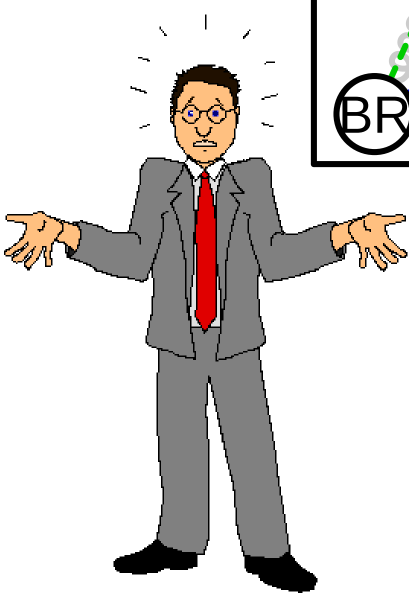




What is the colour flow?

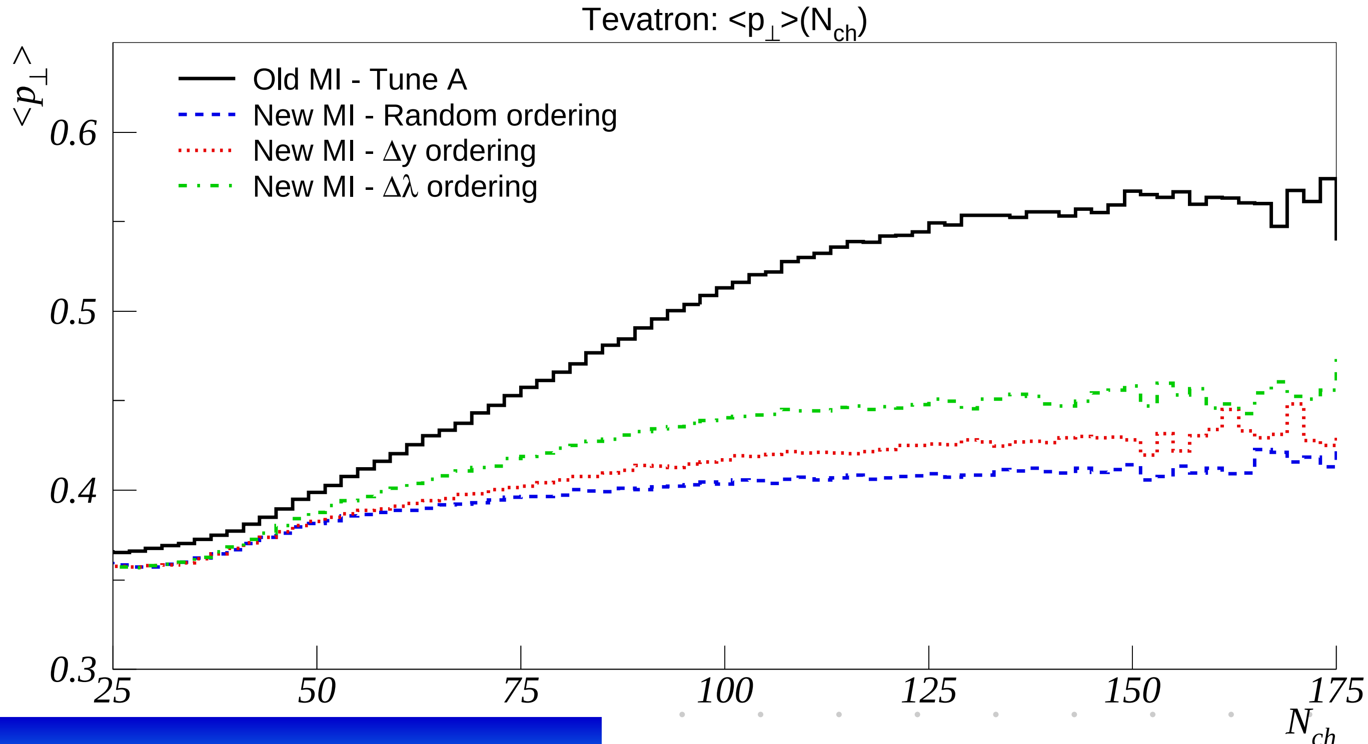
Hooking it up

- Physical colour flow.

  + possible non-perturbative ordering mechanisms:

- Minimization of total potential energy (string length).
- Formation of composite objects in beam remnant (e.g. diquarks).

Some possibilities are (PYTHIA 6.3):



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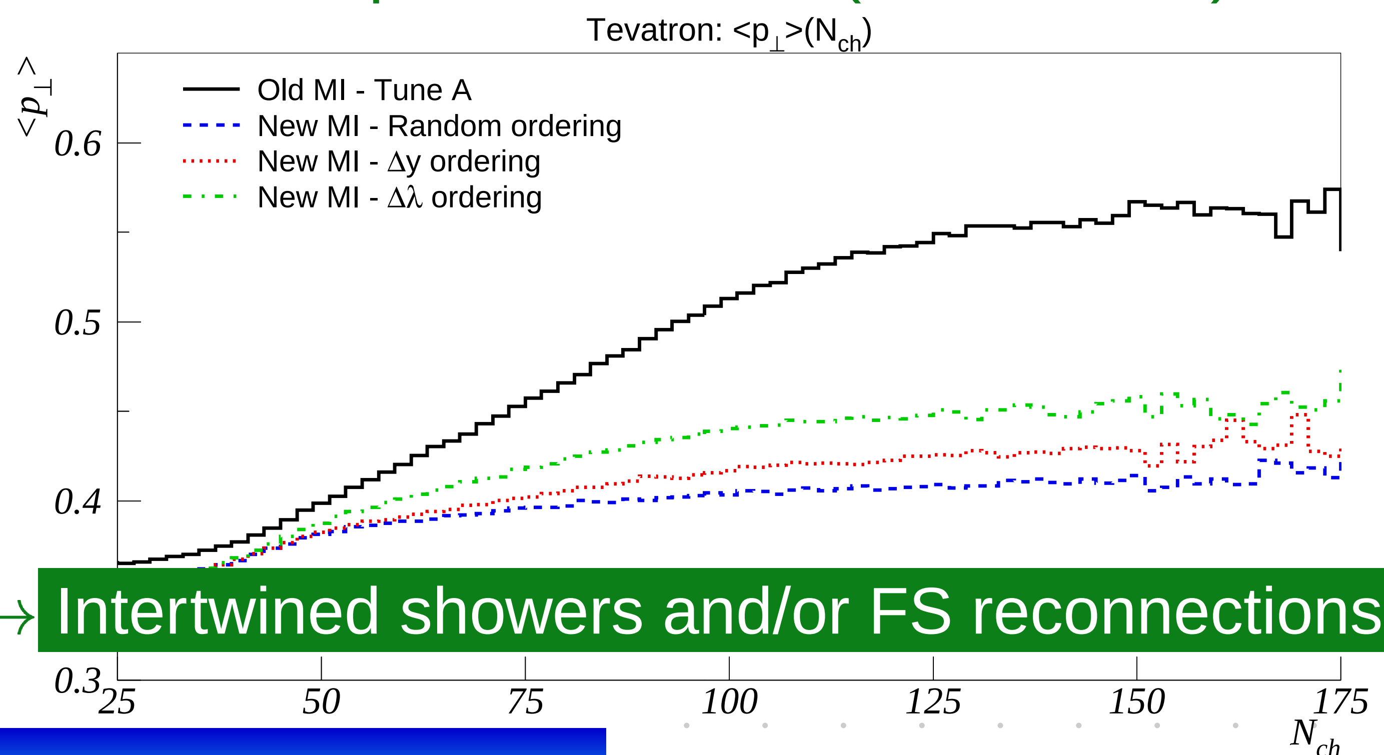


→ Intertwined showers and/or FS reconnections ?

Primordial $k_\perp$ and B.R. kinematics

✧ Correlated primordial $k_\perp$.

Assume gaussian distributed primordial $k_\perp$ for each initiator:

$$\frac{\mathrm{d}^2 N}{\mathrm{d}k_x\,\mathrm{d}k_y} \propto e^{-k_\perp^2/\sigma^2(Q)}$$

$\sigma(1\ \mathrm{GeV}) \approx 0.36\ \mathrm{GeV}\ (hadr.)$
$\sigma(10\ \mathrm{GeV}) \approx 1\ \mathrm{GeV}\ (EMC)$
$\sigma(m_Z) \approx 2\ \mathrm{GeV}\ (Tevatron)$

Recoils along colour neighbours or onto all initiators and beam remnant partons equally (MSTP(90)).

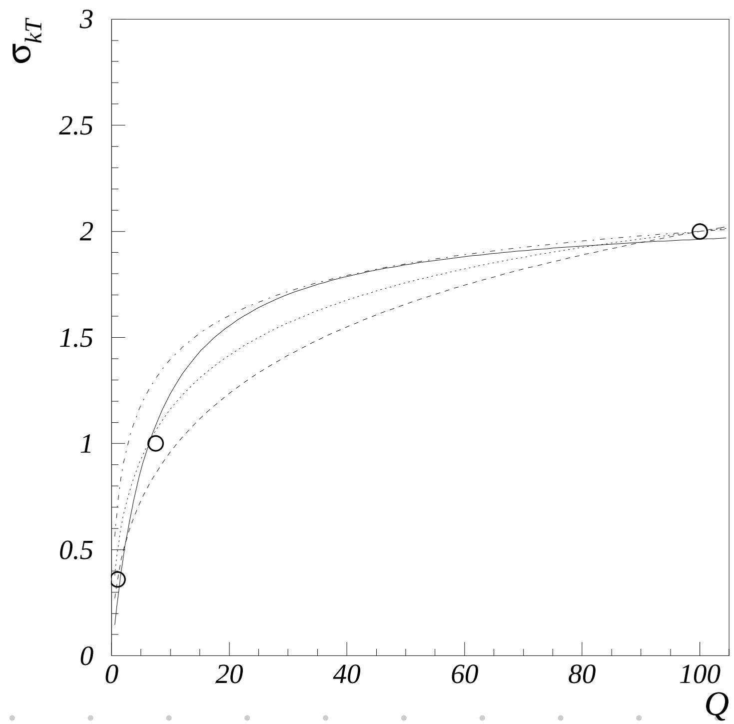
(k_z rescaled to maintain energy conservation.)

Solid: $\frac{2.1Q}{7+Q}$ (hardcoded default)

Dashed: $\frac{4\sqrt{Q}}{10+\sqrt{Q}}$

Dotted: $\frac{3\sqrt{Q}}{5+\sqrt{Q}}$

Dot-dashed: $\frac{2.5\sqrt{Q}}{2.5+\sqrt{Q}}$



Sharing of $\mathrm{x_{rem}}$ in beam remnant

Each hard scattering subsystem has light-cone momenta:

$$\begin{aligned} p_+ &= \gamma(E_1^{CM(z)} + E_2^{CM(z)}) + \gamma\beta(E_1^{CMz} + E_2^{CMz}) \\ &= \sqrt{\tfrac{1+\beta}{1-\beta}\left(\hat{s} + (\vec{p}_\perp^{(1)} + \vec{p}_\perp^{(2)})^2\right)} \\ &= \sqrt{\tfrac{x_1}{x_2}}\sqrt{\hat{s}_\perp} \\ p_- &= \gamma(1-\beta)(E_1^{CM(z)} + E_2^{CM(z)}) = \sqrt{\tfrac{x_2}{x_1}}\sqrt{\hat{s}_\perp} \end{aligned}$$

Remaining light-cone momenta available for BR:

$$p^+_{rem} = \sqrt{s} - \sum_i \sqrt{\frac{x_i^{(+)}}{x_i^{(-)}}\left(\hat{s}_i + (\vec{p}_{\perp i}^{(+)} + \vec{p}_{\perp i}^{(-)})^2\right)} \;\; ; \;\; p^-_{rem} = \sqrt{s} - \sum_i \sqrt{\frac{x_i^{(-)}}{x_i^{(+)}}\left(\hat{s}_i + (\vec{p}_{\perp i}^{(+)} + \vec{p}_{\perp i}^{(-)})^2\right)}$$

Def:"$\pm$" side partons have fractions $x_{j/k}$ of $p^\pm_{rem}$.

- Assume $x_{j,k}$ distributed according to generalized pdf's and fragmentation functions (with (E,p) conserved).
- NB: composite BR systems (w. pion/gluon clouds?) $\rightarrow$ larger x?

Outlook – Multiple Interactions

☞ Overwhelming amount of data confirms basic idea.
(AFS, UA1, UA5, E735, H1, CDF)

☞ Past modelling has consisted of simple parametrizations + some more or less crude/unphysical models.

Much remains uncertain!

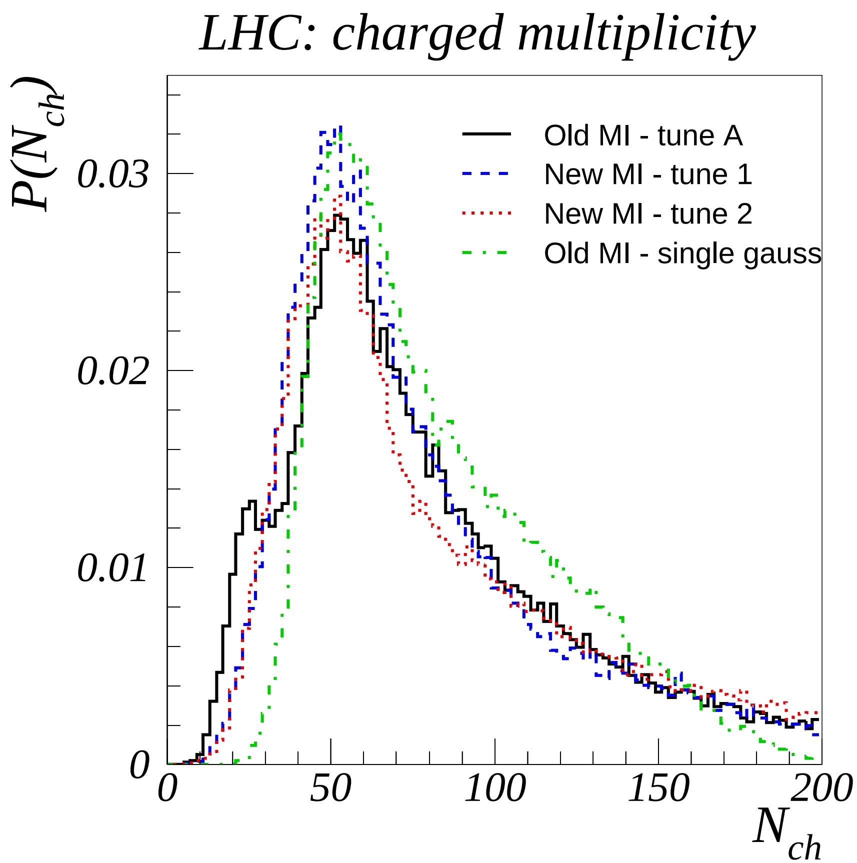
- ★ $p_{\perp\min}/p_{\perp 0}$ cutoff.
- ★ Impact parameter dependence.
- ★ Energy dependence.
- ★ Multiparton densities in incoming hadrons.
- ★ Colour correlations and colour reconnections.
- ★ Interferences between showers.

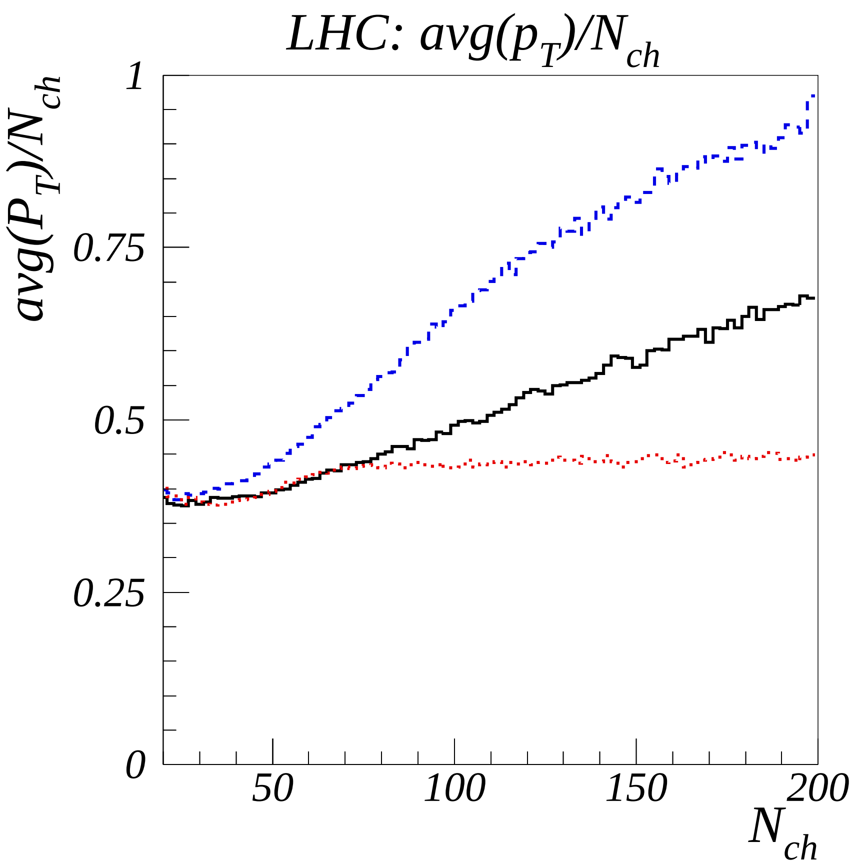
☞ Important to understand for hadronic collisions.

☞ A new physical model for detailed studies available in PYTHIA 6.3. More work in progress.

☞ (Extensions to diffractive topologies, baryon flow in heavy ion collisions, and to meson/photon beams planned.)

Forecast for the LHC (preliminary!)





Tune 1: Example with colour reordering: MSTP(95)=1.

Tune 2: Example without colour reordering: MSTP(95)=0.

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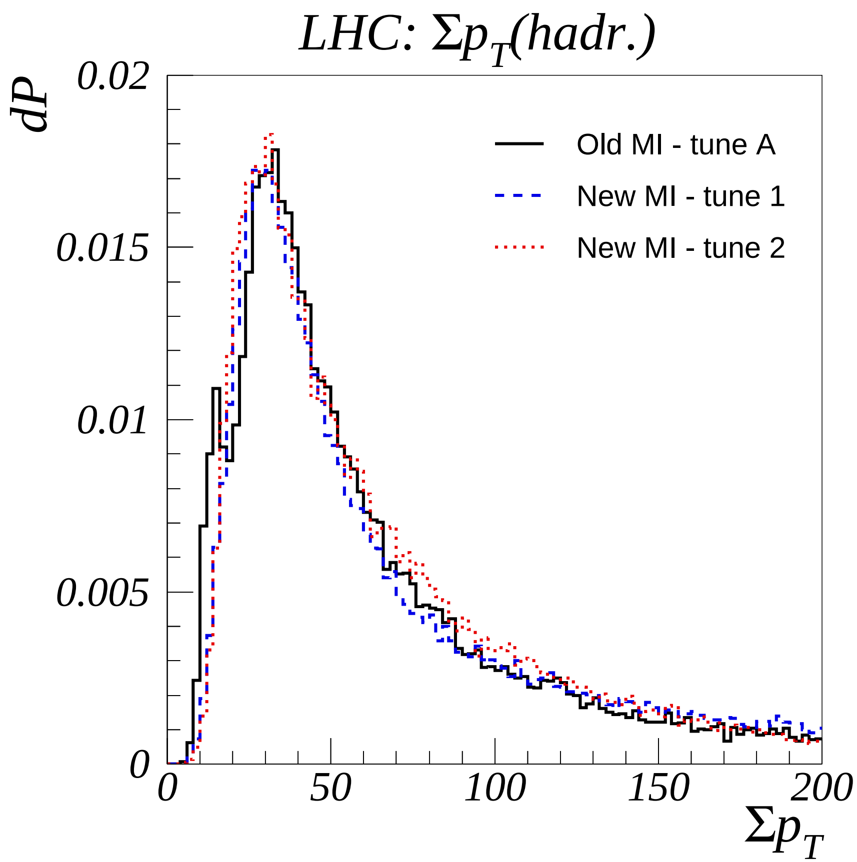

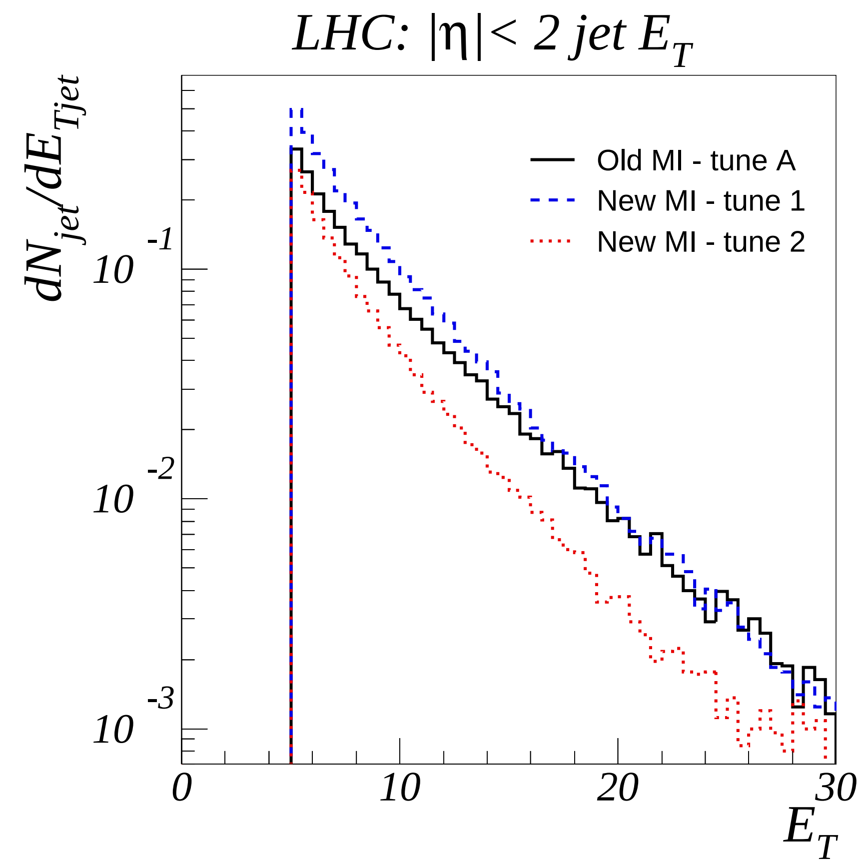

Forecast for the LHC (preliminary!)